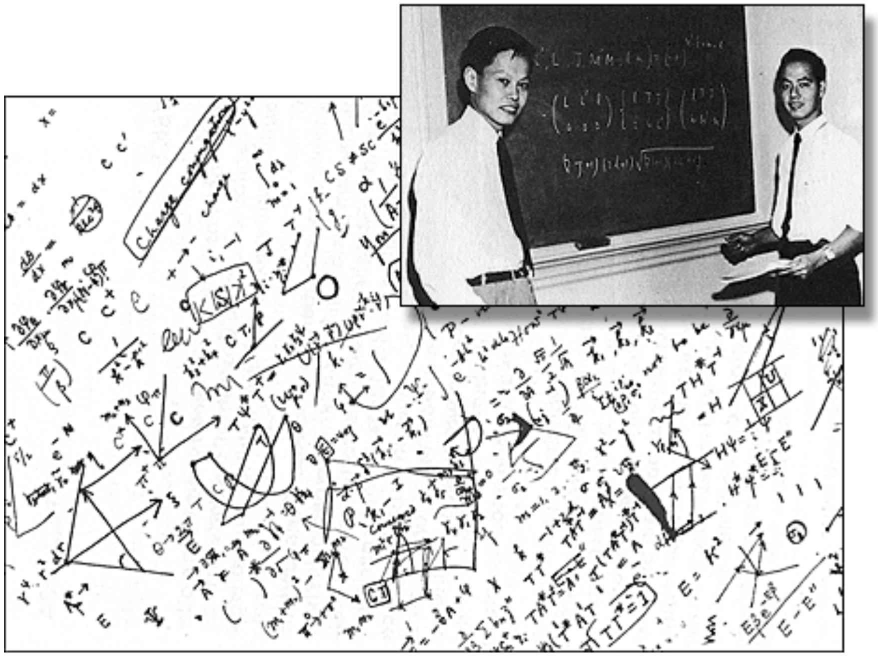
Frontiers in Neutrino Physics

- **Neutrinos as a Probe**
- **Spectra**
- **Intrinsic Properties**
- **Astrophysics/Cosmology/Geophysics**



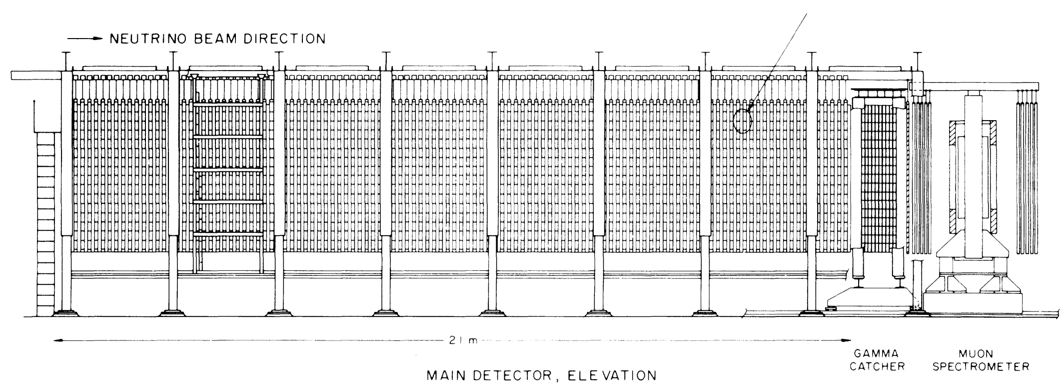


FIG. 1. A schematic drawing of the BNL–Brown–KEK–Osaka–Pennsylvania–Stony Brook neutrino detector.

Neutrinos as a Unique Probe: $10^{-33} - 10^{+28}$ cm

- **Particle Physics**
  - $\nu N, \mu N, eN$ scattering: existence/properties of quarks, QCD
  - Weak decays ($n \to pe^- \bar{\nu}_e, \mu^- \to e^- \nu_\mu \bar{\nu}_e$): Fermi theory, parity violation, quark mixing
  - Neutral current, Z-pole, atomic parity: electroweak unification, field theory, m_t; severe constraint on physics to TeV scale
  - Neutrino mass: constraint on TeV physics, grand unification, superstrings, extra dimensions; seesaw: $m_\nu \sim m_q^2/M_{\rm GUT}$

- **Astrophysics/Cosmology**
  - Core of Sun
  - Supernova dynamics
  - Atmospheric neutrinos (cosmic rays)
  - Violent events (AGNs, GRBs, cosmic rays)
  - Large scale structure (dark matter)
  - Nucleosynthesis (big bang - small A; stars $\rightarrow$ iron; supernova - large N)
  - Baryogenesis
  - Simultaneous probes of ν and astrophysics
- **Interior of Earth**

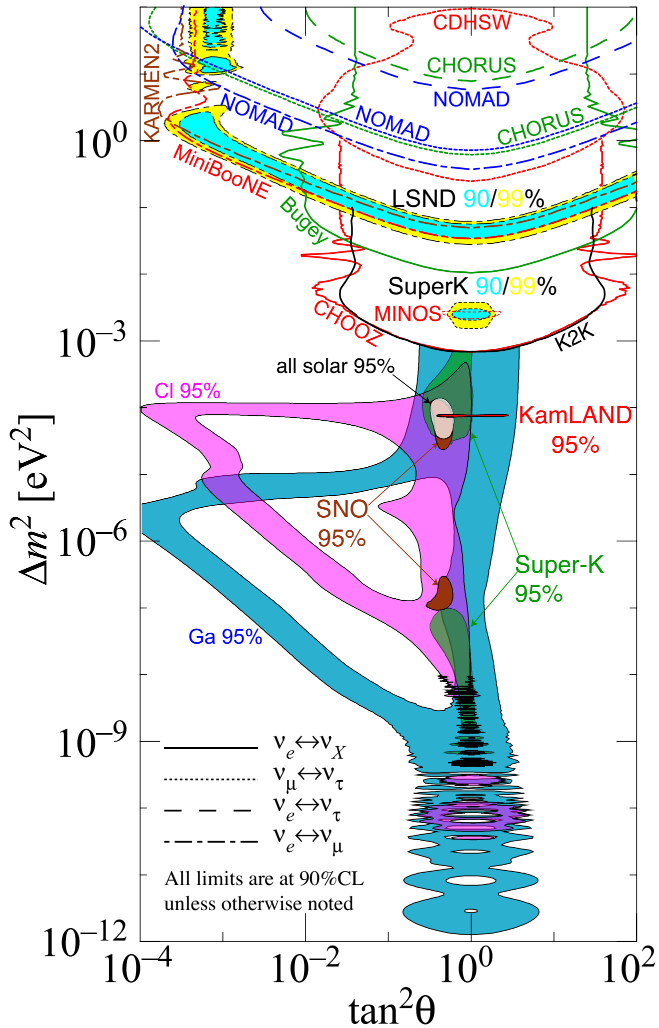
Neutrino Spectra

ν Oscillations

- $P_{\nu_a \to \nu_b} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$

3 ν Patterns

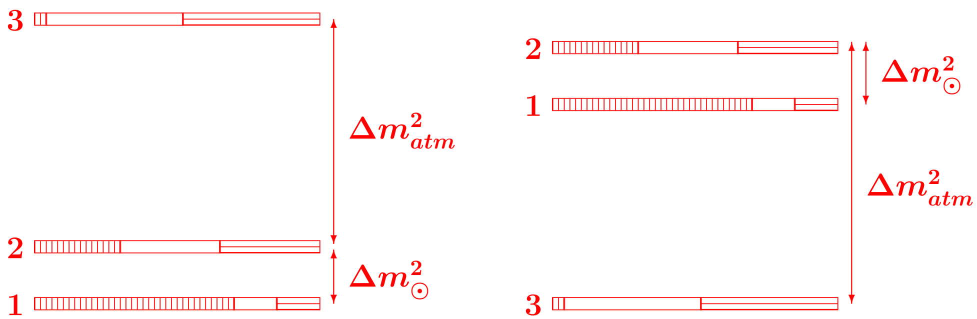
- **Solar: LMA**
  (SNO, KamLAND, Borexino)
- $\Delta m^2_\odot \sim 8 \times 10^{-5}$ **eV^2, mixing large but nonmaximal**
- **Atmospheric + K2K + MINOS:** $|\Delta m^2_{\rm Atm}| \sim 2.4 \times 10^{-3}$ **eV^2, near-maximal mixing**
- **Reactor:** U_{e3} **small**



http://hitoshi.berkeley.edu/neutrino

- **Mixings: let $\nu_\pm \equiv \frac{1}{\sqrt{2}}(\nu_\mu \pm \nu_\tau)$:**

$$\begin{aligned} \nu_3 &\sim \nu_+ \\ \nu_2 &\sim \cos\theta_\odot\, \nu_- - \sin\theta_\odot\, \nu_e \\ \nu_1 &\sim \sin\theta_\odot\, \nu_- + \cos\theta_\odot\, \nu_e \end{aligned}$$



- **Normal hierarchy**
  - **Analogous to quarks, charged leptons**
  - **$\beta\beta_{0\nu}$ rate very small**
- **Inverted hierarchy**
  - **$\beta\beta_{0\nu}$ if Majorana**

- **Degenerate pattern for $|m| \gg \sqrt{|\Delta m^2|}$**

Outstanding Issues (intrinsic properties)

- **Scale of underlying physics?** (string, GUT, TeV?)
- **Mechanism?** (seesaw, LED, HDO, stringy instanton?)
- **Hierarchy, U_{e3}, leptonic CP violation?** (mechanism, leptogenesis)
- **Absolute mass scale?** (cosmology)
- **Dirac or Majorana?** (mechanism, scale, leptogenesis)
- **Baryon asymmetry?** (leptogenesis, electroweak baryogenesis, other?)

Outstanding Issues (intrinsic properties)

- **Scale of underlying physics?** (string, GUT, TeV?) (LHC, flavor)
- **Mechanism?** (seesaw, LED, HDO, stringy instanton?)(indirect: LHC)
- **Hierarchy, U_{e3}, leptonic CP violation?** (mechanism, leptogenesis) (long baseline, reactor, $\beta\beta_{0\nu}$, supernova)
- **Absolute mass scale?** (cosmology) (β decay, cosmology, $\beta\beta_{0\nu}$, supernova)
- **Dirac or Majorana?** (mechanism, scale, leptogenesis) ($\beta\beta_{0\nu}$)
- **Baryon asymmetry?** (leptogenesis, electroweak baryogenesis, other?) (indirect: LHC)

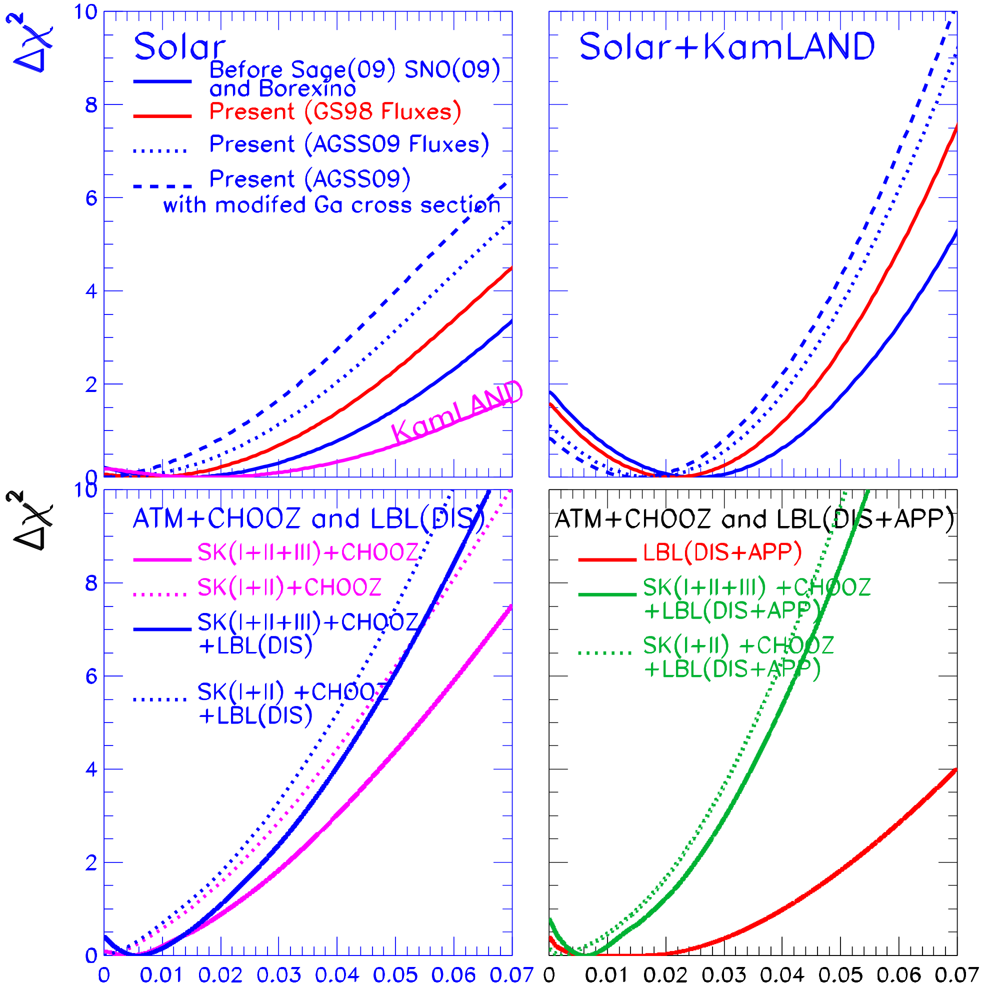
Other properties

- Models
- ν interactions (MINERνA, SciBooNE, SNS [CLEAR], MicroBooNE, NuSOnG)
- Puzzles/anomalies (LSND, NuTeV, MiniBooNE, GSI)
- Quantum subtleties
- Sterile ν's (OscSNS)
- ν decay
- Electromagnetic moments
- Decoherence
- Non-standard interactions
- Neutrino counting
- Heavy ν's
- CPT, Lorentz, equivalence violation
- FCNC (associated $\tilde{\nu}$, $\tilde{\ell}$)
- R_P violation
- $\nu \to \bar{\nu}$
- Mass-varying ν's
- Time-varying ν's
- ν interferometry

U_{e3}, δ_{CP}, hierarchy

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric, } s_{23}^2 \sim \frac{1}{2}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{s_{13}^2 \lesssim 0.035,\ \delta = ?} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, } s_{12}^2 \sim 0.3} \underbrace{\begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana only}}$$

- Need $s_{13} \neq 0$ for leptonic $\not{C}P$ and hierarchy by matter effects



Gonzalez-Garcia,Maltoni,Salvado, 1001.4523

- $s^2_{13} \lesssim 0.035$ **at 90% (CHOOZ reactor $\bar{\nu}_e$ disappearance; global)**
- **Hints for $s_{13} \neq 0$: MINOS (0.7σ excess from $\nu_\mu \to \nu_e$?); Solar vs KamLAND**
- **Future reactor: near and far detectors (s_{13} only)**
  - **Double CHOOZ (France)**
  - **Daya Bay (China)**
  - **RENO (South Korea)**

Long Baseline (LBL) Oscillation Experiments

- 3 ν oscillations, small s_{13} and $\Delta m^2_\odot$ (Akhmedov et al, JHEP 04, 078):

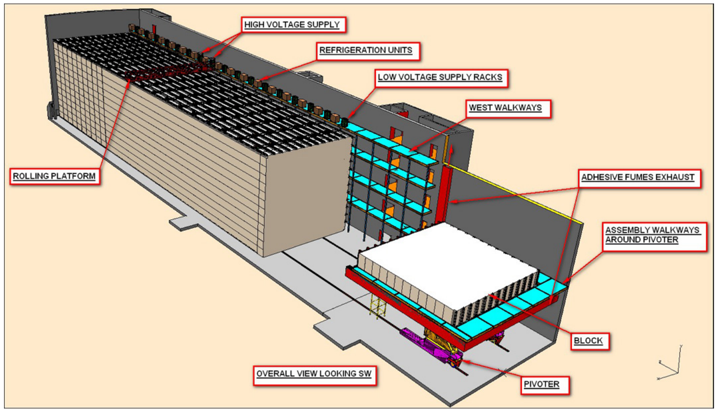
$$P_{\nu_\mu \to \nu_e} = \alpha^2 \sin^2 2\theta_{12}\, c^2_{23} \frac{\sin^2 A\Delta}{A^2} + 4\, s^2_{13}\, s^2_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$
$$+ 2\,\alpha\, s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta) \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1}$$

where

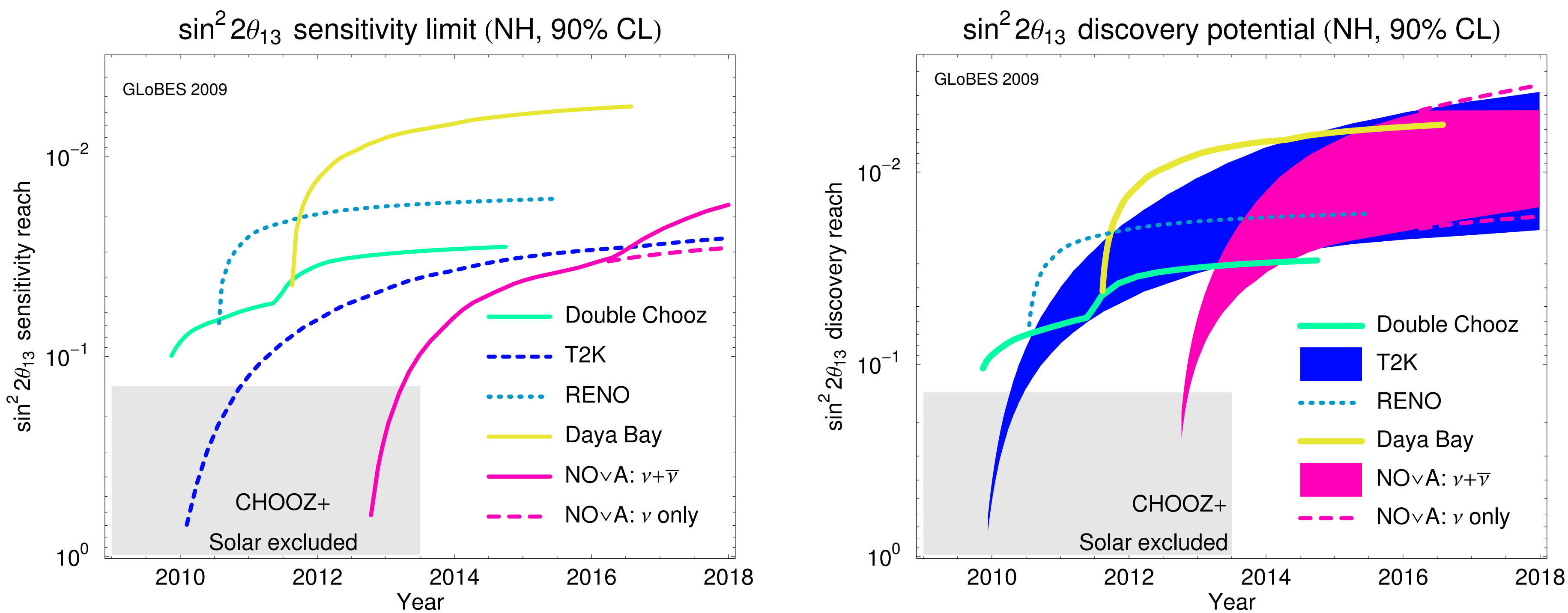
$$\alpha = \frac{\Delta m^2_\odot}{|\Delta m^2_{\rm Atm}|} \sim 0.03, \qquad \Delta = \frac{\Delta m^2_{\rm Atm} L}{4E}, \qquad \underbrace{A = \frac{2\sqrt{2} E G_F n_e}{\Delta m^2_{\rm Atm}}}_{\text{matter}}$$

- $\delta \to -\delta$ and $A \to -A$ for $P_{\bar\nu_\mu \to \bar\nu_e}$
- $\Delta, A > 0$ (normal), $\Delta, A < 0$ (inverted)
- In principle, determine s_{13}, δ, hierarchy (easier if s_{13} from reactor)

experiment	location	L (km)	major mode	status
K2K	KEK–SuperK	250	ν_μ disappear	completed
NUMI-MINOS	Fermilab–Soudan	735	$\nu_\mu, \bar{\nu}_\mu$ disappear	running
T2K	J-PARC–SuperK	295 O/A	$\nu_\mu \to \nu_e$	first events
OPERA	CERN–Gran Sasso	730	$\nu_\mu \to \nu_\tau$	ν_τ observed
NOνA	Fermilab–Ash River	810 O/A	$\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$	construction

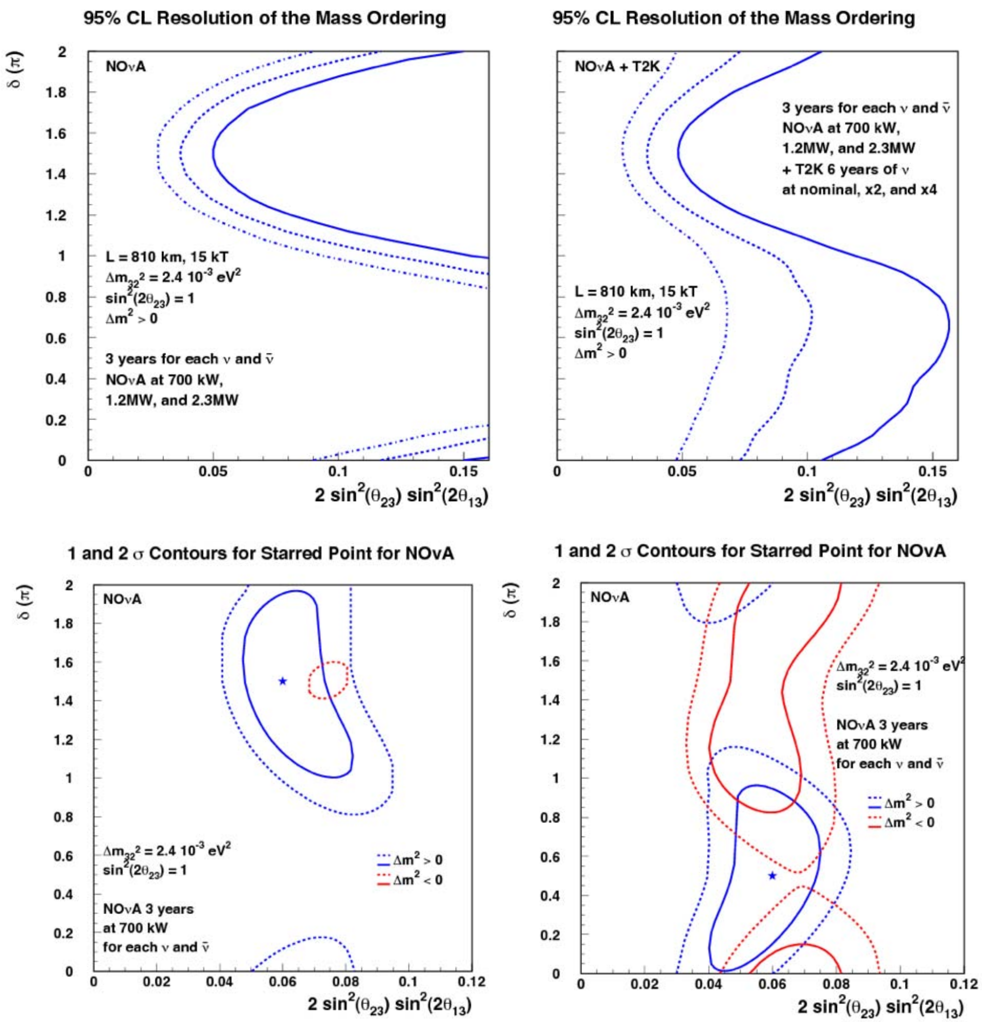


- **Reactor + LBL: $s^2_{13} \sim 10^{-3}$**



Huber, Lindner, Schwetz, Winter, 0907.1896

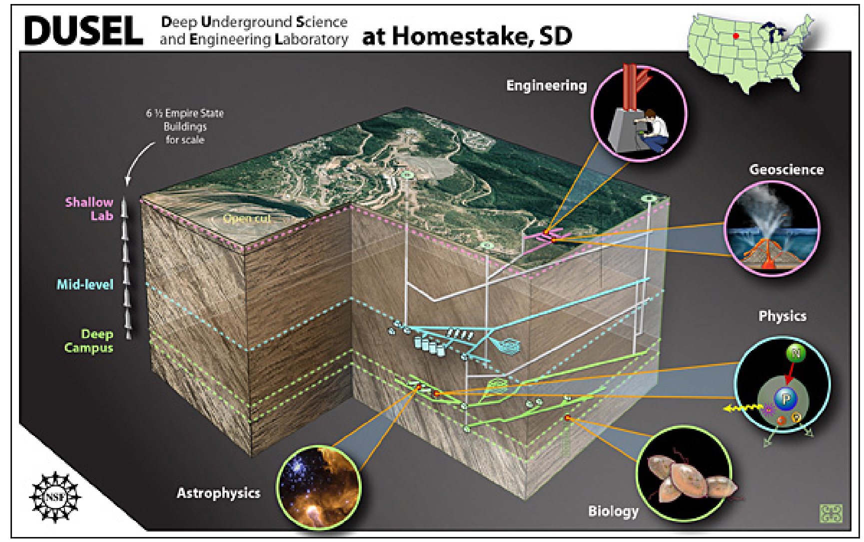
NOνA and T2K

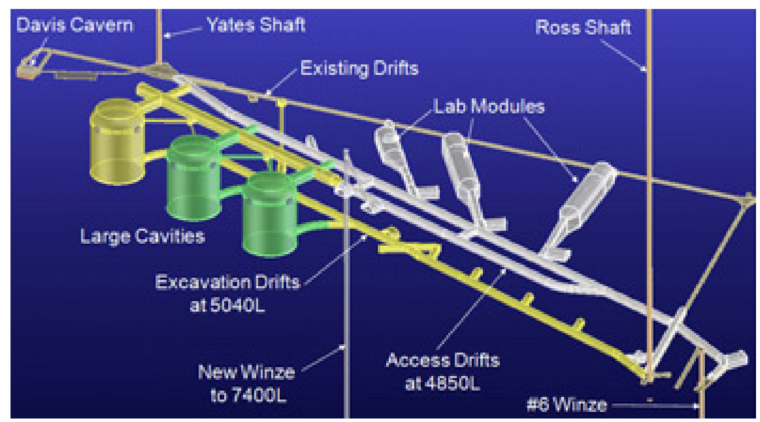


- **Off-axis** (narrow E)
- **NOνA: matter effects from long baseline**
- **NUMI intensity upgrade** (400$\longrightarrow$700 kW)
- **Possible Project X beam upgrade** ($\sim$ 2 MW)
- **Hierarchy and δ indication for favorable parameters**

Long Baseline Neutrino Experiment (LBNE)

- **Fermilab to Deep Underground Science and Engineering Lab (DUSEL)** (1300 km)
- **300 KT water or 100 KT LAr detector** (+ p decay, $\tau \sim 10^{34-35}$ yr)
- **J-PARC to Kamioka + Korea**
- **CERN to ?** (LAGUNA study)
- **Neutrino factory** ($\rightarrow \mu$ collider)
- **β beams**
- **DAEδALUS** (several stopped π beams)





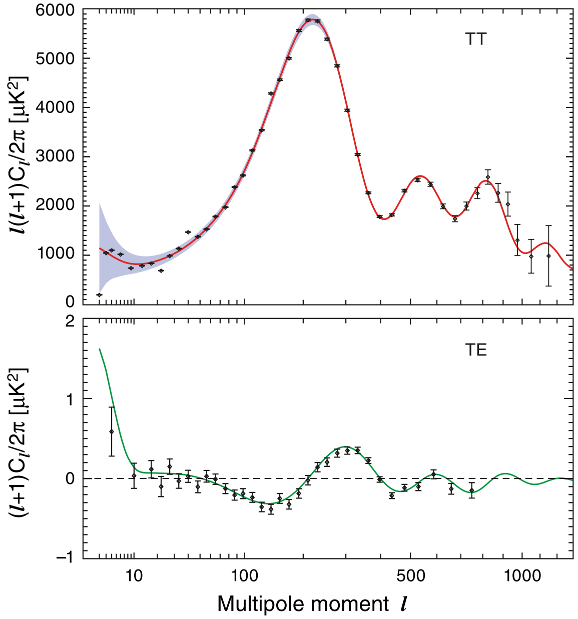
Absolute Mass Scale

- **Tritium β spectrum (KATRIN)**
  $m_{\nu_e} \equiv \left(\sum_i |U_{ei}^2| m_i^2\right)^{1/2} \to 0.2$ eV

- **Cosmology (WMAP7, SDDS, H_0)**
  $\Sigma \equiv \sum_i m_i < 0.58$ eV (95%)

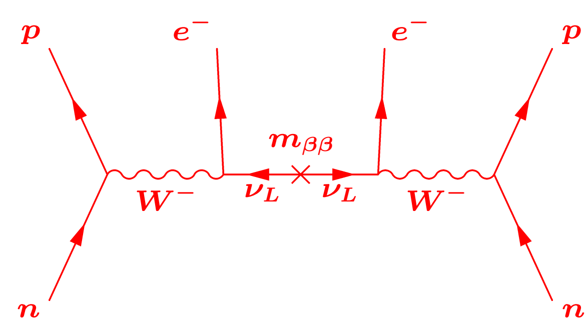
- **Future (Planck, ACTPol, CMBPol)**
  $\Sigma \to 0.05$ eV

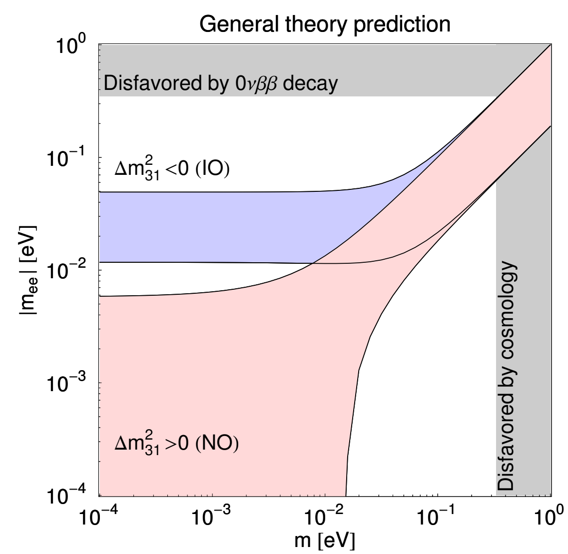
- **$\beta\beta_{0\nu}$ observed** ($m_{\beta\beta} \gtrsim 0.01$ eV) $\to$ **inverted or degenerate**



Dirac or Majorana: Neutrinoless Double β Decay ($\beta\beta_{0\nu}$)

- $nn \to ppe^- e^-$ $(m_{\beta\beta} \equiv \sum_i U_{ei}^2 m_i)$
- **Nuclear matrix element uncertainties** $(\Gamma \sim |A_{nuc} m_{\beta\beta}|^2)$
- **Other mechanisms may dominate** (e.g., SUSY $\not{R}_P$)
- $\subset$ **HDM:** $\tau_{1/2}(^{76}Ge) \sim 2 \times 10^{25}$ y $\to$ $m_{\beta\beta} \sim (0.16 - 0.52)$ eV
- **Cuoricino:** $\tau_{1/2}(^{130}Te) < 3.1 \times 10^{24}$ y (90%) $\to m_{\beta\beta} < (0.19 - 0.68)$ eV (2σ)
- **Future exps sensitive to $\sim$ 0.01-0.02 eV** (inverted or degenerate only)





Winter, 1004.4160

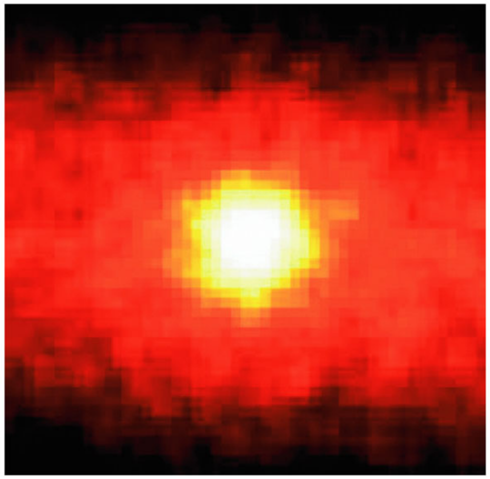
Future $\beta\beta_{0\nu}$ Experiments

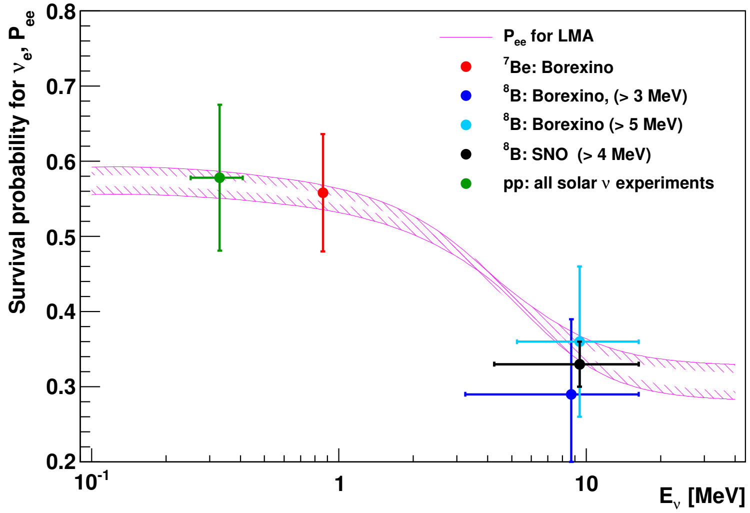
Isotope	$T^{2\nu}_{1/2}$ (10^{19}y)	$T^{0\nu}_{1/2}$ (10^{24}y)	Future Experiment	Mass (kg)	Lab
^{48}Ca	$(4.4^{+0.6}_{-0.5})$	> 0.0014[31]	CANDLES		OTO
^{76}Ge	(150 ± 10)	> 19[22]	GERDA	18-40	LNGS
		$22.3^{+4.4}_{-3.1}$[29]			
		> 15.7[23]	MAJORANA	60	SUSEL
^{82}Se	(9.2 ± 0.7)	> 0.36 [25]	SuperNEMO	100	LSM
^{96}Zr	(2.3 ± 0.2)	> 0.0092[25]			
^{100}Mo	(0.71 ± 0.04)	> 1.1[25]	MOON		OTO
^{116}Cd	(2.8 ± 0.2)	> 0.17[32]			
^{130}Te	(68 ± 12)	> 2.94	CUORE	204	LNGS
^{136}Xe	> 81[33]	> 0.12[34]	EXO	160	WIPP
			KAMLAND	200	KAMIOKA
^{150}Nd	(0.82 ± 0.09)	> 0.0036[35]	SNO+	56	SNOLAB

Cremonesi, 1002.1437

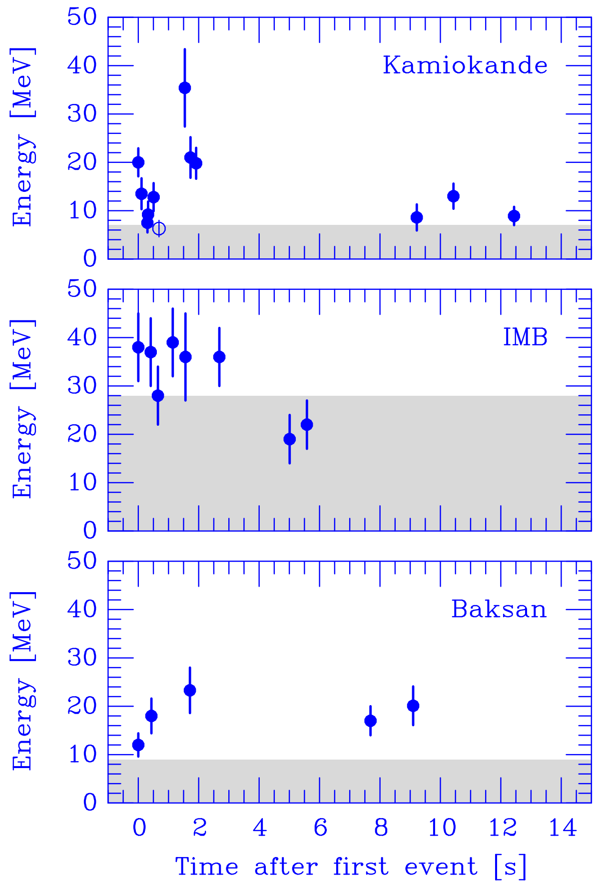
Solar neutrinos

- ν's *and* Sun
- MSW break observed
- pep/CNO neutrinos
- Metallicity conflict
  (helioseismology vs optical)
- Subdominant effects
  (sterile, μ_ν, interactions)
- Borexino, ICARUS, SNO+, LENA





Supernova neutrinos



- Collapse of iron core of $M \gtrsim 8 M_\odot$ star
- 99% of energy ($\gtrsim 3 \times 10^{53}$ ergs) radiated in neutrinos
- Neutronization pulse: $e^- p \to \nu_e n$ (ms)
- Bounce and expanding shock
- Neutrinosphere radiates $\nu_i + \bar{\nu}_i$ ($\sim$ 10 s)
- $\bar{\nu}_e$ observed for SN1987A
  (Large Magellanic Cloud)
  - Confirmed picture of SN dynamics
  - Limits on m_ν, μ_ν, new interactions

- **Expect thousands of events for galactic SN** (30-100 yr)
  - **Detailed study of core-collapse supernova dynamics**
  - **SNEWS: The SuperNova Early Warning System**
    (hours of warning and directionality)
  - **Sensitive to obscured or failed supernovae**
  - **ν hierarchy, small s_{13}, mass scale**
    (MSW, collective effects, time of flight)

- **Keep detectors running for 50 yr!**

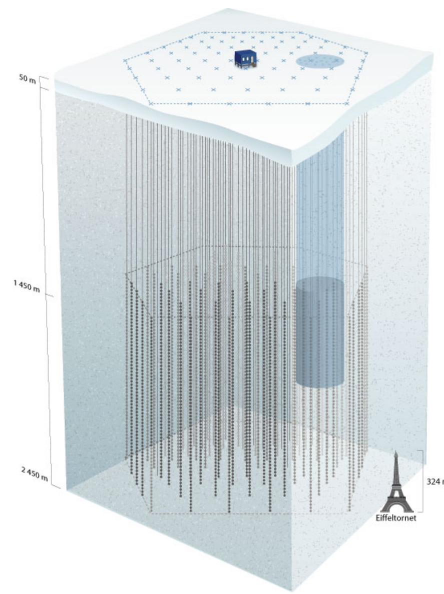
- **Experiments becoming sensitive to diffuse SN ν's from other galaxies**

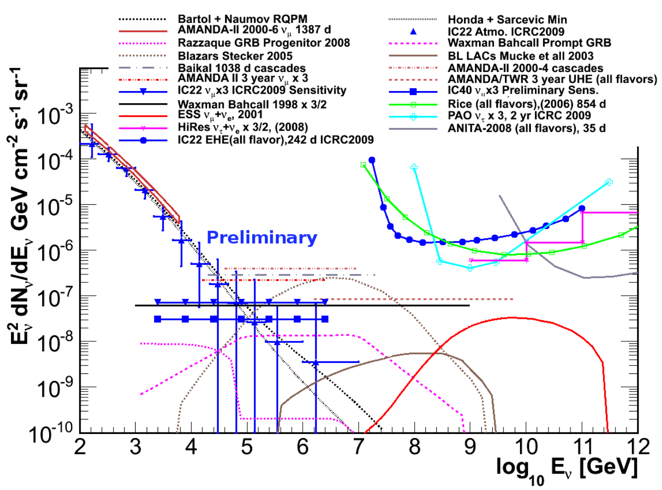
Detector	Type	Mass (kton)	Location	Events at 8.5 kpc	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980-present
Super-K	H_2O	32	Japan	8000	1996-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
MiniBooNE	C_nH_{2n}	0.7	USA	200	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.4/PMT	South Pole	N/A	2007-present
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
HALO	Pb	0.07	Canada	80	Near future
Icarus	Ar	0.6	Italy	230	Near future
NOνA	C_nH_{2n}	15	USA	3000	Near future
LBNE LAr	Liquid argon	5	USA	1900	Future
LBNE WC	H_2O	300	USA	78,000	Future
MEMPHYS	H_2O	440	Europe	120,000	Future
Hyper-K	H_2O	500	Japan	130,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	38,000	Future

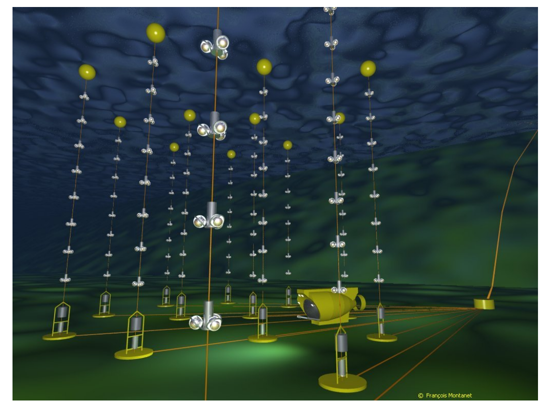
Scholberg, J. Phys. Conf. Ser., 203, 012079

Neutrinos as Cosmic Rays/Secondaries

- **Atmospheric neutrinos**
- **IceCube** (+ Deep Core) **and Antares**
  - **High energy sources** (AGN, GRB)
  - **Dark matter annihilation**
  - **ν spectrum, decay, properties**
  - **Ultra HE ν interactions**
  - **Cosmic ray composition**

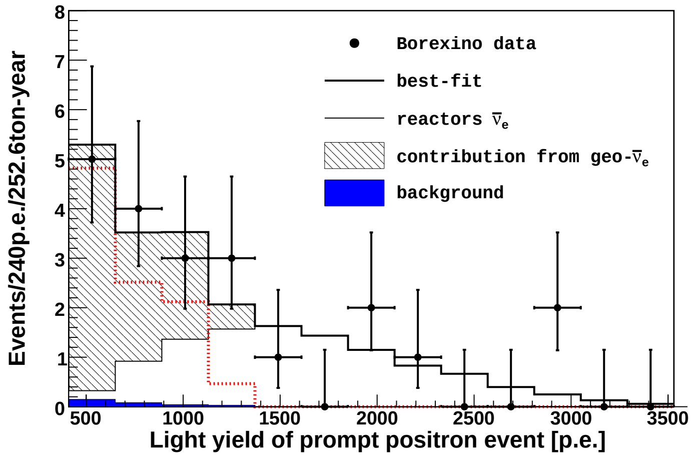






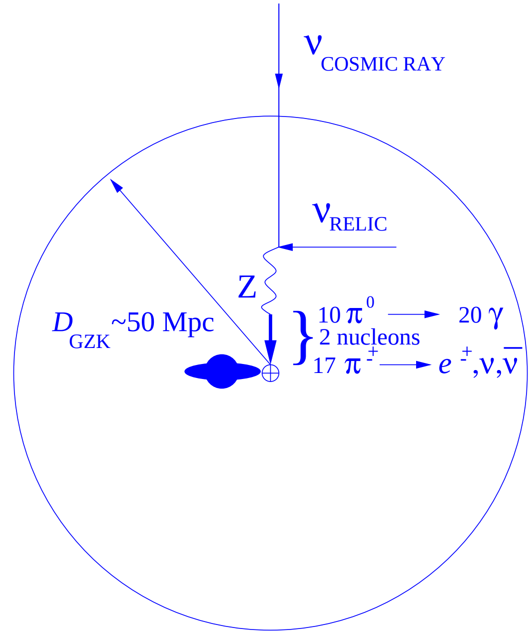
Geoneutrinos

- **Energy output of Earth (30-45 TW) not well understood**
- **Radiogenic heat production:** ($E_{\bar{\nu}_e} < 2.6$ MeV for ^{238}U and ^{232}Th chains)
- **KamLAND observation**
- **Recent Borexino: consistent with observed** (georeactor at core excluded)
- **Future: SNO+, LENA**



The Ultimate Challenge: Relic Neutrinos

- $\nu_i, \bar{\nu}_i$ decoupled at $\sim$ few MeV (relativistic)
- Redshifted to *form* of relativistic thermal distribution
  $\left(T_\nu \sim \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.9K,\ n_{\nu_i} \sim 50/\mathrm{cm}^3\right)$
- Indirect: BBN ($N_\nu = 3.2 \pm 1.2$ at $z \sim 10^{10}$); WMAP7+SDSS+H_0 ($N_\nu = 4.3 \pm 0.9$ at $z \sim 10^3$)



- Direct detection extraordinarily difficult (22^{th} century)
  - Macroscopic forces ($O(G_F^2)$) or torques ($O(G_F)$)
  - ν-induced $e^\pm$ emission by nuclei
  - Z- burst: resonant annihilation of ultra-high energy (10^{22-23} eV) cosmic ν (source? flux?)

Conclusions

- **Neutrino physics is extremely interesting**

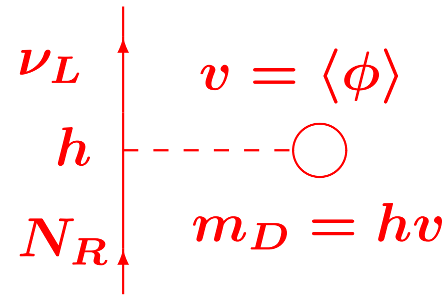
Conclusions

- **Neutrino physics is extremely interesting**
- **Neutrino physics is extremely difficult**

Neutrino Preliminaries

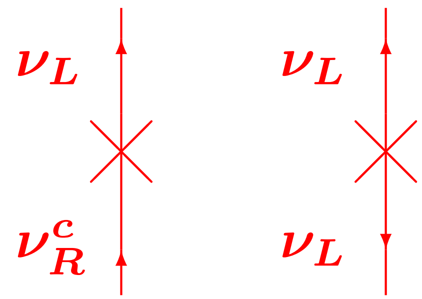
- Weyl fermion
  - Minimal (two-component) fermionic degree of freedom
  - $\psi_L \leftrightarrow \psi_R^c$ by CPT
- Active Neutrino (a.k.a. ordinary, doublet)
  - in $SU(2)$ doublet with charged lepton $\rightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$ by CPT
- Sterile Neutrino (a.k.a. singlet, right-handed)
  - $SU(2)$ singlet; no interactions except by mixing, Higgs, or BSM
  - $N_R \leftrightarrow N_L^c$ by CPT
  - Almost always present: Are they light? Do they mix?

- **Dirac Mass**
  - **Connects distinct Weyl spinors** (usually active to sterile): $(m_D \bar{\nu}_L N_R + h.c.)$
  - **4 components, $\Delta L = 0$**
  - **$\Delta I = \frac{1}{2} \rightarrow$ Higgs doublet**
  - **Why small?** (Large dimensions? Higher-dimensional operators? String instantons?)



- Majorana Mass

  – Connects Weyl spinor with itself:
  $\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.)$ (active);
  $\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.)$ (sterile)

  – 2 components, $\Delta L = \pm 2$

  – Active: $\Delta I = 1$ (triplet or higher-dimensional operator)

  – Sterile: $\Delta I = 0$ (singlet or bare mass)

- Mixed Masses

  – Majorana and Dirac mass terms

  – Seesaw for $m_S \gg m_D$: $m_T \sim M_D^2/m_S$

  – Ordinary-sterile mixing for m_S and m_D both small and comparable